ADVANCED OPTICAL FUZING TECHNOLOGY

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ABSTRACT

We are developing a robust, compact, and affordable photonic proximity sensor for munition fuze applications. Successful implementation of this sensor will provide a new capability for direct fire applications. The photonic component development exploits pioneering work and unique expertise at ARDEC, ARL, and Sandia National Laboratories by combining key optoelectronic technologies to design and demonstrate components for this fuzing application [Ruff, *et al*. 1994; Stann, *et al*. 1996; Simonis, *et al*. 2000; Liu, *et al*. 2000]. The technologies employed in the optical fuze design are vertical cavity surface-emitting lasers (VCSELs), the p-i-n or metal-semiconductor-metal (MSM) photodetectors, and miniature lenses optics. This work will culminate in a robust, fully integrated, g-hardened component design suitable for proximity fuzing applications. This compact sensor will replace costly assemblies that are based on discrete lasers, photodetectors, and bulk optics. It will be mass manufacturable and impart huge savings for such applications. The specific application under investigation is for gun-fired munitions. Nevertheless, numerous civilian uses exist for this proximity sensor in automotive, robotics and aerospace applications. This technology is also applicable to robotic ladar and short-range 3-D imaging.

1. INTRODUCTION

Recent developments in Optical Fuzing technology provided relevant advancement for its application in precision weapons for the Future Combat System ordinance. Optical Fuzing (OF) is a promising alternative approach to standoff fuzing traditionally using RF or RADAR sensing techniques in situations where a highly directional sensor is called for. The inherent directivity of laser emission provides a means of actively sensing targets in cluttered environments. The ability to achieve narrow beam focus allows OF to be used in direct fire munitions. This technology can provide precision Fuzing for both short and long standoff engagements with extremely accurate resolution. Since the laser emission is well focused, the system can remain stealthy and not easily detected or countered from peripheral locations.

The intended targets (both area or point) can be painted with an extremely narrow spot or a large-area beam depending on the application. Keeping a focused and directive targeting source is the major advantage of the optical approach over other fuzing technologies. This narrow beam allows for a direct fire and flat fire feature difficult to accomplish with other types of proximity fuzing schemes. The common RF approach has difficulty eliminating peripheral ground clutter while still sensing the target directly in front of the munition. This clutter resolving capability makes optical fuzing ideal for ordinance traveling near the earth's surface. OF is ideal for missiles or gun-fired munitions requiring standoffs in munition functions at ranges in the 10s of meters or closer with very high range resolution.

An OF system consists of a laser transmitter, an optical receiver, and corresponding electronic signal processors. Figure 1 illustrates a typical implementation of an OF for a gun-fired projectile. Mounted on the front of the projectile, the laser transmits a highly collimated beam that is amplitude modulated with a chirped RF signal at frequency f_{RF}. Photoreceivers are installed on the side of the projectile with their electrical bias modulated at the same time-dependent operational frequency as the transmitted optical signal. As the photoreceivers pick up the reflected optical signal from the target, the on-board signal processor heterodynes

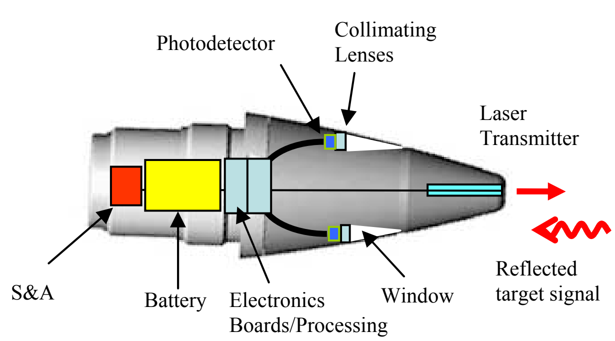

Fig. 1. Illustration of an Optical Fuze for a gun-fired projectile.

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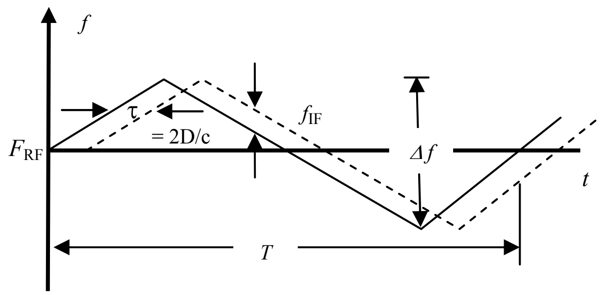

Fig. 2. Waveforms showing the triangularly chirp modulation frequency as a function of time for the transmitted signal (solid) and the returning signal (dashed) with a time delay τ.

(mixes) it with a portion of the delayed transmitted waveform. A distinguished intermediate frequency f_{IF} (or beat frequency) corresponding to the time delay due to the travel time of the light. Measurement of the f_{IF} yields directly the range information of the target. In the case of MSM detector, the mixing is achieved by applied the transmitted chirped signal as a bias to the detector.

Figure 2 shows an example of such a frequency-modulated continuous wave (FM-CW) operation. The transmitted laser beam is operated a frequency f_{RF} with a triangular chirping modulation of Δf over a time period of T. The time delay between the transmitted and reflected waveforms from the target will be $\tau = 2(D/c)$, where D is the distance from the sensor to the target and c is the speed of the light. The range of the target can be determined in the following relation with measured f_{IF}:

$$f_{IF} = \left(\frac{2D}{c}\right)\left(2\frac{\Delta f}{T}\right) = \frac{4D\,(\Delta f)}{cT} \qquad (1)$$

Such a frequency-modulated continuous-wave (FM-CW) operation provides good resolution in both range and frequency over the waveform domain. The corresponding electronic schematic of an OF system is illustrated in Figure 3. An advanced high-power vertical-cavity surface-emitting laser (VCSEL) is employed as the optical transmitter and p-i-n photodiode is employed as the photoreceiver with the mixing process occurring in a separate RF circuit. We are also investigating MSM photodetectors with transimpedance amplifiers as photoreceivers for a self-mixing detector to eliminate the need for an electronic mixer. Such an architecture combines the optical detection and RF mixing into one component and has the advantage of small signal-to-noise (S/N) ratio [Shen, *et al*, 2000].

2. VCSEL AND DETECTOR DEVELOPMENT

In the OF system, an advanced high-power VCSEL is employed as the optical transmitter source. VCSELs combine the capability of high-power output with the superior quality of the laser beam as well as very low fabrication and packaging costs. The laser beam output from the transmitter can further be collimated or focused using external miniature optics to achieve operational requirement. VCSELs can also be readily flip-chip hybridized onto associated electronics. MSM photodetectors/mixers provide advantages of fast

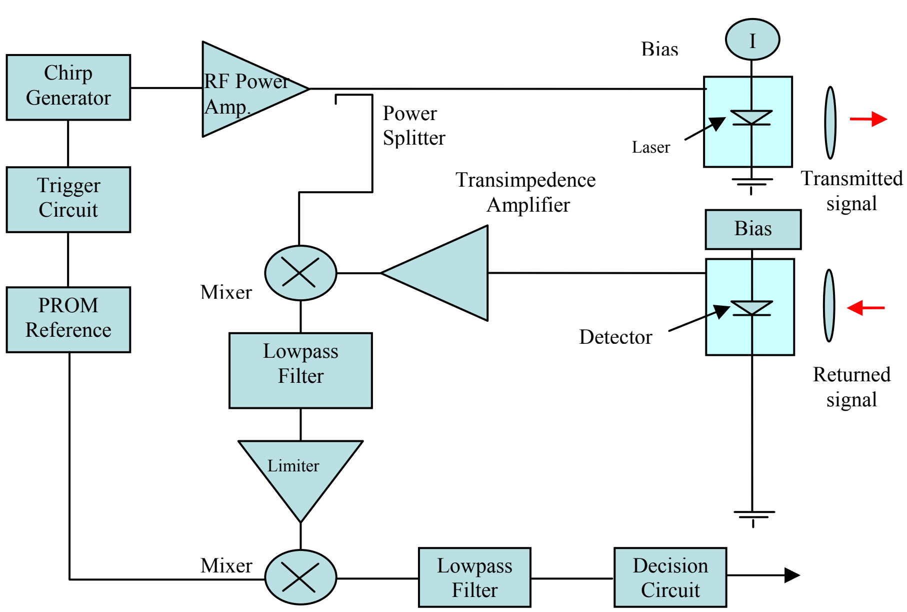

Fig. 3. A block diagram of the electronics processing system for an Optical Fuze.

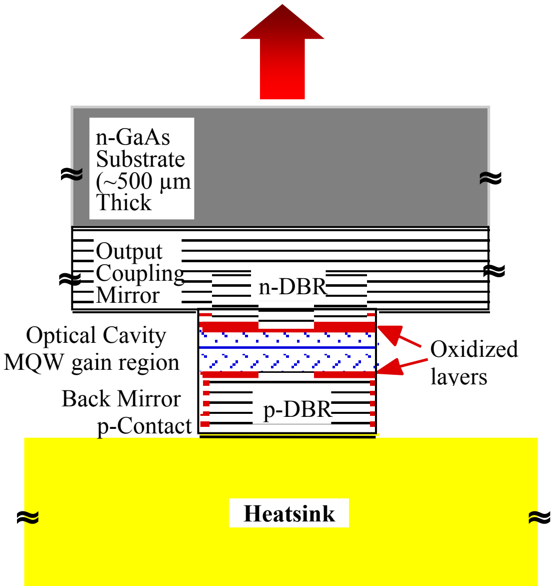

Fig. 4. The cross-sectional structure of a VCSEL flip-chip bonded on a heat-sinking substrate.

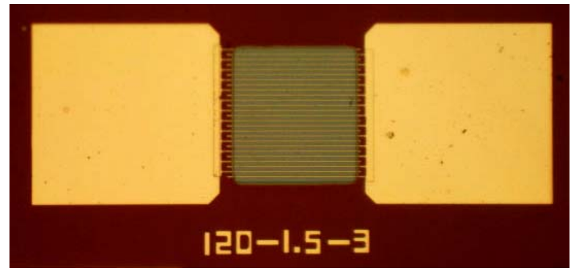

Fig. 5. Micrograph of an InGaAs MSM photodetector whose active area has 10 pairs of interdigitated fingers and a finger spacing of 3 µm.

responsivity and simplicity in structure and operation. MSM photoreceivers can function as detectors and mixers and operate directly in FM-CW mode with simplified electronic circuits for signal processing.

2.1. 980-nmVCSEL Fabrication

The VCSEL heterostructures were grown by metal-organic chemical vapor deposition (MOCVD) on an n^+-GaAs substrate [Geib, *et al.* 2002]. The VCSELs consist of an active quantum-well gain region embedded between two distributed Bragg reflectors (DBR). A more detailed description of our VCSEL structure is provided in Figure 4 where it is portrayed in a flip-chip mount onto heat-sinking or CMOS driver electronics substrates. The typical mirror composition consists of a 36-period GaAlAs/$Al_{0.9}Ga_{0.1}As$ *p*-doped high-reflectivity DBR and a 25-period GaAlAs/$Al_{0.9}Ga_{0.1}As$ *n*-doped output DBR. The active region consists of three undoped $In_{0.2}Ga_{0.8}As$ quantum wells and GaAs barriers, centered in $Al_{0.4}Ga_{0.6}As$ spacer layers to form a single-wavelength cavity. The emission wavelengths for different VCSELs with somewhat different quantum-well thicknesses are in the range of 970 to 980 nm. Two $Al_{0.98}Ga_{0.02}As$ layers are placed in the VCSEL structures above and below the active region for selective lateral oxidation to provide optical and electrical confinement. A typical high-power VCSEL device used in the present prototype fuze study has a 40-µm mesa diameter and a 18-µm oxidized aperture.

2.2. InGaAs MSM photodetectors

Interdigitated-finger metal-semiconductor-metal (MSM) devices have widely been used as high-speed photodetectors due to their simple structure, high response speed, low dark current, and processing compatibility with other semiconductor devices [Aliberti, et al. 2004]. When used as a detector, a dc bias voltage is applied to the MSM device. As photons are absorbed, electron-hole pairs are created, and the conductivity of the semiconductor increases. The detector operates by registering the number of carriers swept out of the device per unit time by the applied field, i.e., by measuring the photocurrent. The electrodes are designed in such a way as to maximize light transmission into the semiconductor and, at the same time, minimize carrier transit time. Interdigitated-finger MSM detectors can also be used as optoelectronic (OE) mixers to generate radio-frequency subcarriers in fiber-optic microwave links. When used as a mixer, the intensity-modulated optical signal is simultaneously detected and mixed with the modulated electrical bias to obtain the difference frequency, f_{if}. This frequency conversion is obtained with an ac bias voltage applied to the device, i.e., a local-oscillator (LO) signal. Figure 5 illustrates a top view of a MSM photodetector structure.

2.3. Characterization of VCSEL and PD Devices

Electrical current-voltage-optical power (I-V-L) measurements for such devices showed a current threshold between 4 to 5 mA and operating voltage of 1.5 to 2.5 volts. Such current threshold is quite acceptable for the CMOS driving circuits that are used with the VCSELs. The maxium dc output power achieved was around 10 mW. The pulsed ac operation using 1 µs pulses demonstrated a power output of 40 mW. More optical power output can be achieved by increasing the

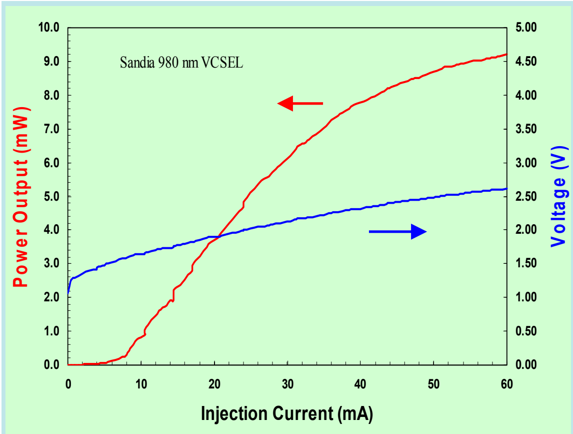

Fig. 6. Current-Power and Current-Voltage characteristics of a high-power VCSEL device.

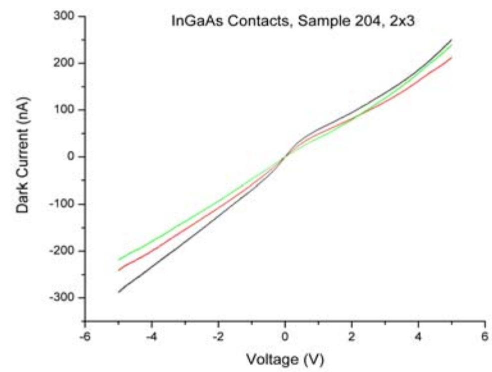

Fig. 7. IV characteristics of a MSM photodetector.

size of the aperture and applying appropriate heat-sinking techniques. Figure 6 shows the current-voltage-optical-power characteristics of a such VCSEL device.

The wavelength of the VCSEL output was measured to be 970 nm. GaAs-based MSM photodetectors are not efficient enough for operation at this wavelength. Standard InGaAs MSM photodetectors have an excessive leakage current. It is therefore necessary to design an optimized resonant-cavity InGaAs MSM structure. The resonant-cavity MSM-PD OEM structure, grown via molecular-beam epitaxial technology, consists of a 930 Å GaAs cap layer, a 1000 Å InGaAs absorption layer, a 930 Å GaAs layer, a 829 Å AlAs layer, and 15 layers each of 695 Å GaAs/829 Å AlAs (this is the DBR) all grown on a GaAs substrate. The electrodes consist of Ti/Au Schottky contacts deposited via electron-beam evaporation. The electrodes have 1.5-µm finger widths and 3-µm spacings.

The intrinsic dark current-voltage (I-V) characteristics for this MSM structures are shown in figure 7. The figure shows the dark current for the metal deposition directly on the top GaAs cap layer. Based on these results, we decided to fabricate further devices with the metal deposition directly on GaAs cap layer due to the much lower dark current. One issue that might arise from this type of fabrication is the degradation in mixing efficiency due to the capacitance of the GaAs layer. Such results have been observed in previously characterized InGaAs-based MSMs with Schottky enhancement layers.

3. INTEGRATED OPTOELECTRONIC FUZES

The sensor in a proximity fuze for a missile or projectile application initiates warhead detonation when the projectile comes within a desired range from the target where the warhead will produce maximum damage. For optical sensors, range can be determined with geometric and opto-electronic ranging technologies. The simplest technology is geometric ranging, which relies on ranging effects inherent in the limited transmitter/receiver overlap regions or parallax in the field of view combined with an appropriate amplitude threshold in the return signal. Optical sensors have been built and fielded over the years for a variety of applications using this approach. However, it is not always possible to meet stringent requirements using this geometric approach. When the requirements cannot be met using this approach, the solution is to use opto-electronic ranging. This approach requires higher bandwidth components and greater signal processing capabilities. Opto-electronic ranging is useful to generate the ranging function for a long-range system where the transmitter and receiver beams overlap for considerable distances and geometric parallax systems would have significant ambiguity.

4. OPERATION OF OPTICAL FUZES

The ranging theory applied for the optical fuze is an adaptation of frequency modulation CW (FM-CW) radar ranging principles. In the simplest sense, the laser transmitter is amplitude modulated with a radio-frequency sub carrier which itself is frequency modulated in time. The target reflected light is incoherently detected with a photodiode and converted into a voltage waveform carrying the time-dependent time-delayed modulation frequency of the return signal. This waveform is then further processed to recover the target range, as shown in equation (1) and the basic electronic block diagram of the sensor architecture in figure 3.

The divergent laser beam is transmitted through a lens that collimates the light and directs it toward the target. A small portion of the transmitted light is reflected

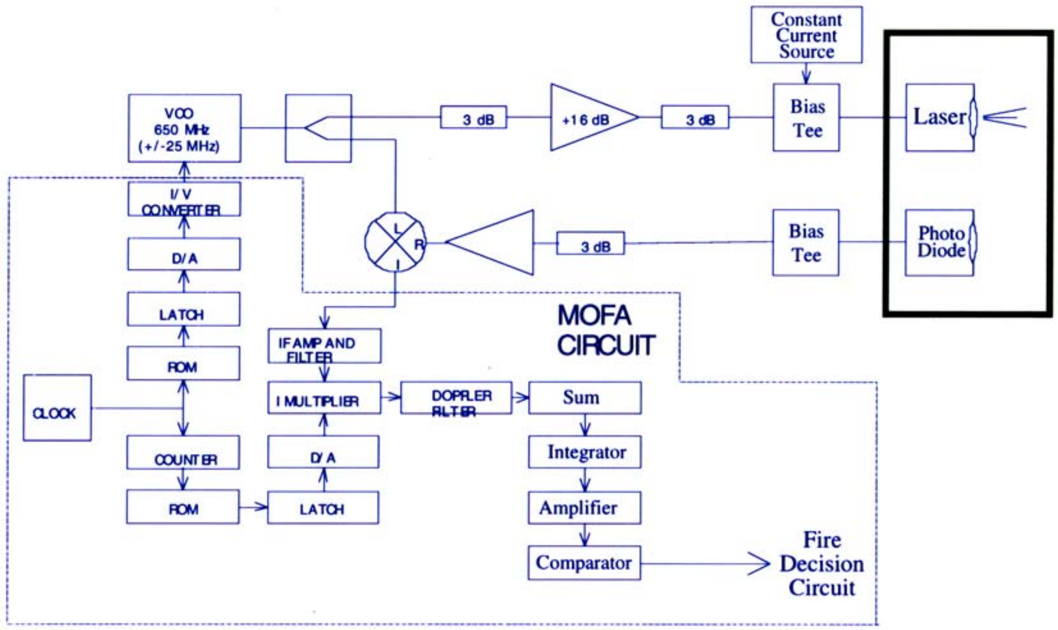

Fig. 8. A block diagram of the ladar (laser radar) optical sensor system that applied to optical fuze.

from the target back toward the sensor, collected by a lens, and focused down onto the active region of a photodetector. The photodetector converts the incident light power into a current waveform with amplitude proportional to the light power, or equivalently, the original chirp waveform. The current waveform is converted into a voltage waveform by a wideband transimpedance amplifier. The output of the amplifier is mixed with an undelayed sample of the transmitted chirp waveform and the output of the mixer is fed into a low pass filter to recover an intermediate frequency (IF) signal f_{IF}.

In most implementations of the sensor a trigger circuit initiates the generation of a modulation waveform that will persist for some time and cycle in a time period of *T*. The chirp signal can be simply a sinusoidal waveform whose frequency of modulation increases or decreases over time, *T*. For the architecture described here, the chirp signal may have a start frequency in the tens to low hundreds of megahertz and a stop frequency in the hundreds of megahertz. The difference between the start and stop frequency, ΔF, is chosen to establish the desired range resolution ΔR. It can be found that $\Delta R = c/(2\Delta F)$**,** where c is the velocity of light. The chirp signal is fed into a wideband rf amplifier that modulates the current driving a solid-state laser diode with bandwidth at least equal to the chirp waveform.

A laboratory sensor was constructed to demonstrate the concept viability. A block diagram of the ladar (laser radar) optical sensor system that is suitable for the OF is shown in figure 8. A section of the Multi-Option Fuze for Artillery (MOFA) processor was used with an optical transceiver. The MOFA processor generates a triangle wave, which is used to modulate the output of a voltage-controlled oscillator (VCO). The peak-to-peak level of the wave determines the modulation bandwidth and the dc level is used to set the center frequency. The result is a FM-CW signal centered at 650MHz, with a bandwidth of +/- 25MHz (frequencies used where for an implementation of a lab prototype used for demonstration purposes). The VCO output is divided using a power splitter. Half of the signal is mixed with the target return signal to produce an intermediate frequency (IF). The remaining signal is amplified and used to modulate the constant current source that drives the laser diode. An FM-CW waveform is used to modulate the laser in order to provide more accurate range resolution within the processor. The bias tee circuit is used to provide an impedance match between the amplifier and the laser. The laser emits a beam of light, the intensity of which is proportional to the drive current. The light is collimated by a lens system onto the target. The transmitted light reflects off the target and back to a second lens system, which focuses the light onto the active region of the photodetector. The photodiode produces a current, which is proportional to the intensity of the return signal. This current is converted into a voltage and amplified. The amplified signal is mixed with a portion of the original VCO output to produce the IF signal which is processed by the MOFA circuit to determine target range.

5. SUMMARY

To date we have demonstrated a lab system capable of ranging to 25 meters with commercially available edge-emitting laser and photodiodes. With these commercial parts greater distances are achievable with higher power laser source with larger optical apertures. However, for this fuzing application and given packaging and size constraints, neither path is available as a solution. We have collected results on VCSEL and MSM components to exploit these devices. Selected components have been flight-tested and air gun tests have demonstrated survivability performance to 40 KGs acceleration. The commercially available components do not meet our long-term power efficiency and bandwidth requirements needed to realize adequate performance. They also fall short in cost and size requirements. Our goal is to capitalize on VCSELs and MSM photodetectors advancement to produce a compact, low-cost gun-rugged optical fuze.

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